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(54) Title: DATA PROCESSING SYSTEM WITH SYNCHRONIZATION COPROCESSOR FOR MULTIPLE THREADS
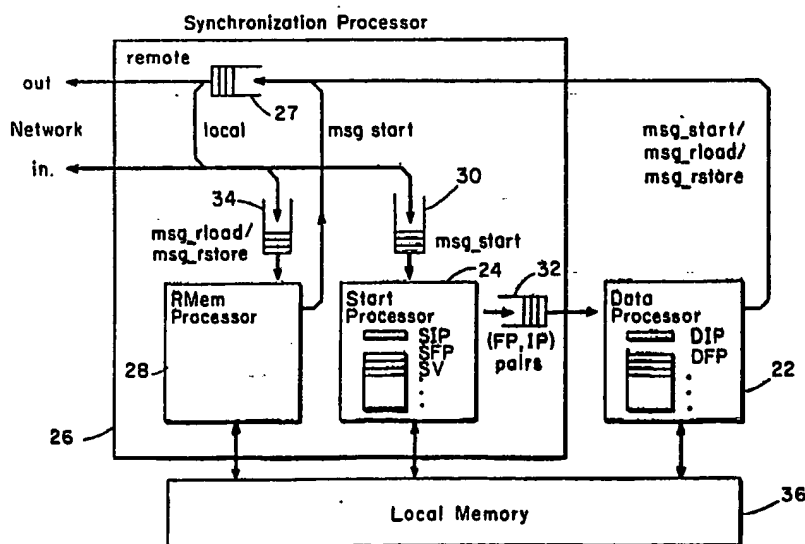
(57) Abstract

A multiprocessor system comprises a plurality of processing nodes, each node processing multiple threads of computation. Each node includes a data processor which sequentially processes blocks of code, each block defining a thread of computation. The code includes instructions to send start messages with data values to start new threads of computation. Each node also includes a synchronization coprocessor for processing start messages from the same and other nodes of the system. The coprocessor processes the messages from a message queue to store values as operands for threads of computation, to determine when all operands required for a thread of computation have been received and to provide in a continuation queue an indication to the data processor that a thread of computation may be initiated. The data processor subsequently nonsynchronously initiates the thread of computation. Alternatively, a single processor may perform the continuation and message processing functions in an interleaved sequence. The data processor creates messages to remote nodes using a global virtual address which is translated before transmission to a node designation and a local virtual address at the remote node.

Data Processing System with Synchronization
Coprocessor for Multiple Threads

Background of the Invention

Many are interested in the goal of general purpose
computing that achieves very high speeds by exploiting
parallelism in a scalable, cost-effective way. There
seems to be widespread consensus that the architecture of
such machines will be composed of a number of nodes
interconnected with a high speed, regular network, where
each node is built with an off-the-shelf microprocessor.
Because such machines are built out of commodity parts,
and because the topology is scalable, it is felt that
such a machine with hundreds or thousands of nodes will
be cheaper and faster than classical supercomputers,
which are built with exotic technology and are thus very
expensive.

To date, the prevailing opinion seems to be that
microprocessors have their own evolutionary momentum
(from CISC to RISC and, now, to a multiple instruction
issue), and that a massively parallel machine will simply
track this wave, using whatever microprocessors are
currently available. However, a massively parallel
machine is in fact a hostile environment for today's
micros, arising largely because certain properties of the
memory system in a massively parallel machine are
fundamentally different from those assumed during the
evolution of these micros. In particular, most micros
today assume that all memory is equally distant, and that

memory access time can be made effectively small by cacheing. Both these assumptions are questionable in a massively parallel machine.

On the other hand, dataflow processors have been designed from the start by keeping in mind the properties of the memory system in a parallel machine. However, past dataflow processor designs have neglected single-thread performance, and hence must be classified as exotic, not the kind of processor to be found in commodity workstations.

To be cost-effective, the micros used in massively parallel machines should be commodity parts, i.e., they should be the same micros as those used in workstations and personal computers. Market forces are such that a lot more design effort can be expended on a stock microprocessor than on a processor that is sold only in small quantities. In addition, there is a question of software cost. Parallel programs are often evolved from sequential programs, and will continue to use components that were developed for single-thread uniprocessors (such as transcendental function libraries, Unix, etc.). This does not mean that we are restricted to using good, conventional microprocessors in any parallel machine that we build. All it means is that any new processor that we design for multiprocessors must also stand on its own as a cheap and viable uniprocessor.

Parallel programs contain synchronization events. It is well known that processor utilization suffers if it busy-waits; to avoid this, some form of multiplexing amongst threads (tasks or processes) is necessary. This is true even in uniprocessors.

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In order to build parallel machines that are
scalable both physically and economically, we must face
the fact that inter-node latency in the machine will grow
with machine size, at least by a factor of log (N), where
N is the number of nodes in the machine. Thus, access to
a non-local datum in a parallel machine may take tens to
hundreds of cycles, or more. If we are to maintain
effective utilization of the machine, a processor must
perform some other useful work instead of idling during
such a remote access. This requires that the processor
be multiplexed amongst many threads, and that remote
accesses must be performed as split transactions, i.e., a
request and its response should be treated as two
separate communication events across the machine. If we
follow this argument a step further, we see that a
communication entering a node will arrive at some
relatively unpredictable time, and that we need some
means of identifying the thread that is waiting for this
communication. This is, in fact, a synchronization
event.

Thus, the following picture emerges. In a parallel
machine, the way to deal with long inter-node latencies
is exactly the way to deal with synchronization. A
program must be compiled with sufficient parallel
slackness ("excess parallelism") so that every processor
has a pool of threads instead of a single thread, and
some threads are always likely to be ready to run. Each
processor must be able to multiplex itself efficiently
amongst these threads. All communications should be
split transactions, in which (a) an issuing processor
does not block to await a response, and (b) a receiving

processor can efficiently identify and enable the thread
that awaits an incoming communication. For a more
thorough explication of this argument, please refer to
Arvind and R. A. Iannucci, "Two Fundamental Issues in
Multiprocessing," Proceedings of DFVLR - Conference 1987
on Parallel Processing in Science and Engineering,
Bonn-Bad Godesberg, W. Germany, Springer-Verlag LNCS 295,
June 25-29, 1987.

Modern von Neumann microprocessors are excellent
single-thread processors, but they are not designed to
exploit parallel slackness efficiently. First, the cost
of multiplexing amongst threads is high because of the
enormous processor state that is associated with the
currently executing thread. This state manifests itself
in the register set and instruction and data caches, all
of which may have to be reloaded with the new thread's
context. Second, for a parallel environment, there is no
efficient mechanism for naming, communicating and
invoking continuations for split transactions to access
remote locations. Third, many first-generation parallel
machines had very poor interfaces to the interconnection
network. There was a large software cost in handling
incoming messages. This was further aggravated by the
fact that messages trying to cross a node had to go
through the node. However, many of the successors of
these machines have solved this problem somewhat by
devoting separate resources to message handling.

The net result is a high communication and
synchronization cost with von Neumann machines. Programs
can be written to use these machines effectively provided
they minimize the occurrence of communication and

synchronization events, and there are many success
stories that do so. However, there is a high software
cost associated with trying to structure programs to fit
this model, and it is still a far cry from our goal of
truly general purpose computing.

Dataflow architectures have evolved substantially
over the years. We will focus our comments on Monsoon
(G. M. Papadopoulos, "Implementation of a General-Purpose
Dataflow Multiprocessor," PhD thesis, Laboratory for
Computer Science, Massachusetts Institute of Technology,
Cambridge, MA 02139, August 1988; G. M. Papadopoulos and
D. E. Culler, "Monsoon: An Explicit Token Store
Architecture," Proc. 17th Intl. Symp. on Computer
Architecture, Seattle, WA, May 1990 and U.S. patent
application Serial No. 07/396,480) as the most recent
representative of that evolution.

Dataflow architectures are excellent at exploiting
parallel slackness. Indeed, this has always been a major
underlying rationale for dataflow architectures.
Parallel slackness is achieved by partitioning a program
into extremely fine grain threads; in the pure dataflow
model, each instruction is a separate thread. A thread
descriptor is implemented as a token, which includes
three parts (FP,IP,V), where:

    o   FP is a frame pointer, which points at a frame
        relative to which the instruction will be
        executed;

    o   IP is an instruction pointer, which points t
        code; and

    o   V is a data value.

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The pool of threads in a processor is manifest at a
token queue. On each cycle, a token is extracted from
the token queue, and the instruction to which it refers
is executed by the processor relative to the frame to
which it points. Every instruction explicitly names its
successor instruction(s). As a result of this execution,
zero, one, or two successor tokens are produced, which
are placed back in the token queue. Thus, a dataflow
processor like Monsoon can multiplex between threads on
every cycle.

Split transactions are performed thus: when a
processor wishes to read a remote location A, it executes
a fetch instruction. This causes a "read" token to be
constructed and injected into the network. Suppose the
fetch instruction names label L as its successor
instruction. The corresponding read request token
contains the following information:

(READ, A, FP, L)

Once the read request token is sent out, the processor
continues to execute other tokens in its token queue.
When the read request token reaches the remote memory,
the following token is sent back:

(FP, L, V)

This token is placed in the token queue to be executed
just like any other token.

In addition, Monsoon also has an efficient mechanism
to synchronize two threads. Two threads that must join

will arrive at a common instruction that names a frame
location which contains "presence bits", which can be
regarded as a synchronization counter. On arrival, each
thread causes the counter to decrement. When the first
thread arrives, the counter does not reach its terminal
value; the instruction is aborted and the processor moves
on to execute another token from the token queue. When
the second thread arrives, the counter reaches its
terminal value and the instruction is executed.

Thus, dataflow architectures (and Monsoon in
particular) provide good support for exploiting parallel
slackness - fine grain threads, efficient multiplexing,
cheap synchronization, and support for split transactions
to mask inter-node latency.

However, present dataflow architectures do not have
good single-thread performance. The fundamental problem
is that present dataflow architectures do not provide
adequate control over the scheduling of threads. In the
pure dataflow model, successive tokens executed by the
processor may refer to arbitrarily different frames and
instructions. The consequence is that an instruction can
transmit values to its successors only through slow
memory - it cannot exploit any special high speed storage
such as registers and caches. In conventional
uniprocessors, caches allow fast transmission of values
because the successor instruction is executed
immediately, while a previously stored value is still in
the cache. This locality through successor-scheduling is
absent in pure dataflow models. Pure dataflow models
allow exactly one value to be transmitted without going
to memory - the value on the token.

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Monsoon improves on this situation. In Monsoon, an instruction can annotate one of its successors so that it is executed directly, i.e., instead of placing the token back into the token queue, it is recirculated directly into the processor pipeline. Thus, in a chain of such direct successors, instructions can communicate values down the thread via high speed registers - no other thread can intervene to disturb the registers. However, Monsoon still has some engineering limitations that limit single-thread performance, namely, (a) very few registers (only three) and (b) the processor pipeline is eight cycles long, so that each instruction in a chain takes eight cycles.

In Monsoon, control over scheduling stops at this point. A chain of direct successors is broken when it reaches an instruction that is a split transaction instruction (like a load), or when it reaches an instruction that executes a join that fails. At this point, there is no further control on the next thread to be executed. If we had such control, we might, for example, choose another thread from the same frame, to maintain locality with respect to the current frame.

Disclosure of the Invention

The present invention provides the fast single-thread execution of conventional micros, coupled with the facilities to exploit parallel slackness from dataflow architectures. In addition, we provide tight control over the scheduling of threads.

In accordance with one aspect of the present invention, a von Neumann data processor processes

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individual blocks of code sequences as threads of
computation to be performed with respect to frames of
data. Those threads of computation include operations to
generate messages for initiating new threads of
computation. A synchronization coprocessor processes the
messages with respect to frames of data and indicates to
the data processor when a new thread of computation may
be performed.

In accordance with another aspect of the invention,
the data processing system comprises a continuation queue
of continuations which identify blocks of code sequences
to be performed with respect to frames of data. It also
includes a message queue of messages which identify
blocks of code sequences to be performed with respect to
frames of data. Data processing means is provided with
processing individual blocks of code sequences identified
by continuations from the continuation queue as threads
of computation. Threads of computation include
operations to generate messages for initiating new
threads of computation. The data processing means also
processes individual blocks of code sequences identified
by messages from the message queue as message handlers.
The data processing means may be implemented as a single
data processor or as coprocessors. If implemented as
coprocessors, those coprocessors may individually process
separate instruction sequences under control of separate
sequencers, or they may share a common sequencer which
directs instructions to one or the other of the
coprocessors.

Preferably, a continuation comprises a pointer to an
activation frame and a pointer to a data processing

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instruction. Similarly, a message comprises a pointer to
an activation frame and a pointer to a synchronization
instruction.

In a multiprocessor system comprising a plurality of
processing nodes, each node processes multiple threads of
computation. In a preferred addressing approach, each
data processing node operates on a local virtual address
space, and each node has means for translating from the
local virtual address space to a local physical address
space. Further, each data processing node generates a
global virtual address to access an address in a remote
node, and each node comprises means for translating the
global virtual address to a node designation and a local
virtual address of the remote node.

Each data processor sequentially processes threads
of code. In the preferred system, the code includes
local memory load and store instructions, start
instructions which cause start messages to be sent with
data values to start new threads of computation and
remote memory load and store instructions which cause
messages to be sent to remote memory locations to fetch
or store data from or in remote memory locations. The
synchronization processing means processes start messages
to store values from the start messages as operands for
threads of computation, to determine when all operands
required for a thread of computation have been received
and to provide an indication to the data processor that a
thread of computation may be initiated.

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Brief Description of the Drawings

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

Figure 1 is a schematic illustration of a single node of a multiprocessor embodying the present invention.

Figure 2 illustrates the transmission of start messages between plural nodes of a data processing system.

Figure 3 illustrates transmission of a remote load message to a remote node and return of a start message.

Figure 4 presents the code for performing the SAXPY routine.

Figure 5 illustrates an improved version of the SAXPY code.

Figure 6 is a more detailed illustration of the system of Figure 1 employing a Motorola 88110 microprocessor.

Figure 7 illustrates global and local address translation in accordance with the present invention.

Figure 8 is a detailed illustration of the Start Processor of Figure 6.

Figure 9 is a detailed illustration of the increment and test logic of the Start Processor of Figure 8.

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Figure 10 is a reservation table illustrating timing of operations within the pipeline of Figure 8 relative to instructions in response to a start message.

Figure 11 is a state diagram of an alternative embodiment of the invention using a single sequencer for processing both messages and data threads.

Figure 12 is a block diagram of an alternative embodiment of the invention which uses coprocessors controlled by a common sequencer.

Figure 13 is a detailed block diagram of the synchronization units of Figure 12.

Figure 14 illustrates the protocol of a message in the system of Figures 12 and 13.

Description of a Preferred Embodiment

In most languages, when a procedure is invoked,

o   a frame (also known as an activation record) must be allocated for it;

o   arguments (if any) must be deposited in its frame; and

o   execution of its code must be initiated.

When it terminates, it passes results to the frame of its continuation, and initiates computation there (usually, this is its caller). During execution, the frame is generally stored in registers.

In a parallel system, a procedure may invoke several other code blocks in parallel. Further, iterations of a loop may also be invoked in parallel and be distributed across the nodes of the machine. Where previously a loop ran in a single frame, we may now have to allocate separate frames for each iteration or group of

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iterations. In general, instead of a stack of frames, we
now have a tree of frames. Because frames may now
correspond both to the procedure invocations and to loop
iterations, we prefer to use the term code block for the
segment of code that is the unit of invocation.

We are going to use frames as the basis for
locality. Frames may be distributed among the nodes of
the parallel machine, but each frame must reside entirely
within a single node. There is no such restriction on
global data structures - a single object may span several
nodes of the machine. For each frame in a node, the
corresponding code block must also be present in that
node. This means that if a code block is invoked in
several nodes, copies of that code block must exist in
all those nodes. A simple way to achieve this is to copy
all code into all nodes, but code blocks could also be
loaded dynamically on demand. The key point is that a
particular invocation of a code block can always access
its frame locations using local memory operations.
Accessing locations in other frames or in global objects,
however, may involve communication. This will be
reflected in the instruction set of the processor in each
node.

The *T (pronounced "start") model embodying the
present invention for a node in a parallel machine is
shown in Figure 1. Although the memory of the machine is
physically distributed amongst all the nodes, we assume a
single global address space, i.e., the local memory in a
node implements a piece of a single address space.

The Data Processor 22 is a superset of a
conventional RISC processor, with a conventional
repertoire of register-to-register instructions, and

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ability to manipulate local memory using conventional load and store instructions. Its program counter is called DIP ("Data processor Instruction Pointer"). One of its registers, called DFP, is assumed to contain a pointer to the "current frame" which is always in its local memory. Being a conventional RISC processor, the Data Processor 22 is optimized to run long, sequential threads efficiently. It obtains the starting points of these threads from a Start Processor 24 of a Synchronization Processor 26. On completion of a thread, if there is no new thread available from the Start Processor, the Data Processor simply waits until a thread becomes available. Clearly, for good utilization, this situation should be avoided.

In addition to its conventional RISC instructions, the Data Processor can execute a few additional "dataflow instructions" whose effect is to send messages into the network through a queue 27. These are non-blocking sends, i.e., the Data Processor continues executing after sending a message. The message can cause threads to be scheduled on the other nodes or on the same node, and a later response may deposit values in the sender's frame. As discussed below, by including a message formatter in the Synchronization Processor, the Data Processor can be a fully conventional RISC processor.

We will look at messages in more detail shortly, but for the moment it is enough to know that each message has the form:

msg_op arg1, arg2, ...

Arg1 is always a global address that identifies a unique
destination node in the parallel machine. The message is
automatically routed there. Of course, messages to the
current node are short-circuited back directly. Broadly
speaking, msg_ops fall into two categories: "start"
messages and "remote memory" messages. Start messages
ultimately initiate processing of a thread by the data
processor. Remote memory messages serve to write or
fetch data into or from memory; fetched data is
ultimately returned to the requesting node with a start
message. For convenience, the two types of messages are
handled by separate processors within the synchronization
processor, but a single processor may be used. When a
message arrives at a node, it is passed either to the
Start Processor 24 through a queue 30 or to an RMem
Processor 28 through a queue 34 based on the category of
it msg_op.

The Start Processor has a program counter called SIP
("Start processor Instruction Pointer"), two special
registers SFP and SV and, perhaps, other general purpose
registers. The Start Processor is triggered by the
arrival of a start message from a queue. It simply waits
if there is no start message available. When it picks up
a start message, its SIP, SFP and SV registers are loaded
with values from the message, after which it begins
executing instructions from the address in SIP. It can
read and write local memory 36 and it can post new thread
identifying (FP, L_D) pairs to a queue 32 to be picked up
by the Data Processor in initiating new threads of
computation. FP is a frame pointer and L_D is a pointer
to the block of code for the thread.

Because both the Start Processor and the Data
Processor may execute instructions, we will distinguish
labels for the two processors by the subscripts S and D,
respectively.

The instruction set of the Data Processor is a
proper superset of a conventional RISC instruction set,
so we will assume the reader is familiar with
conventional arithmetic-logic and comparison
instructions, unconditional and conditional jumps, etc.
We will focus here only on the novel, dataflow
instructions that have to do with threads and
synchronization. While reading the descriptions below,
please refer to Figure 2 for an overview of the
thread-related instructions and messages.

A common situation where we wish to start a new
thread is when one code block F calls another code block
G. For example, we may wish to transport an argument
from F's frame to G's frame and to initiate a thread in G
that will compute with it. Similarly, we may wish to
transport a result back from G's frame to F's frame and
to initiate a thread in F to compute with it. In
general, these frames may be on different nodes, so we
need an explicit communication to perform these actions.
For this, we use a start instruction, which has three
register arguments:

Data Processor Instruction: start rF, rI, rV
    Semantics: Let FP = Register [rF]
                       Let L_S = Register [rI]
                       Let V = Register [rV]
                       Send message: msg_start FP, L_S, V

Note that the start instruction is effectively a fork,
since the Data Processor continues to execute at the next
instruction after it has initiated the message send.
Note also that this is only the first half of a one-way
communication, i.e., the start instruction only emits a
msg_start message. In other words, the start instruction
is a non-blocking send. The instruction pointer L_S on
the start message is a label for a Start Processor, not a
Data Processor.

Readers familiar with dataflow literature will
recognize that the contents of a msg_start message
correspond exactly to a classical dataflow "token" - FP
is the "context", L_S is the "statement" and, of course, V
is the value.

The fork instruction is a special case of the start
instruction in which the destination frame is the same as
the current frame, and no data value is transmitted. Of
course, in this case, no message need be sent into the
network - the msg_start message is short-circuited back
directly to the local Start Processor:

       Date Processor Instruction: fork rI
       Semantics: Let L_S = Register [rI]
                        Let FP = Register [DFP]
                        Send message: msg_startv FP, L_S, foo

where foo is an arbitrary value.

At this point, it is worth making some observations
that contrast the start instruction with other models of
forking threads.

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    o   The start instruction does not involve any
resource allocation. In many other fork
models, a fork involves the dynamic allocation
of a new stack. In our model, dynamic resource
allocation is separated out into a completely
orthogonal issue, and the start instruction is
very cheap - it just sends a simple message.

    o   In many fork models, each fork is a sequential
thread associated with a stack with possibly
multiple frames. In our model, every frame can
have multiple threads active in it. In fact,
there is no limit to the number of threads
active within a frame.

The Data Processor can terminate a thread and begin
executing a new one by executing a next instruction:

Date Processor Instruction: next
Semantics: A new frame pointer FP and
                              a new instruction pointer L_D
                              are loaded from the Start
                              Processor into the Data
                              Processor into DFP and DIP
                              registers.

The Data Processor thus continues fetching and executing
instructions from L_D.

As discussed below, the data flow specific start,
fork and next instructions can be implemented by
conventional RISC instructions load and store (fetch and
write) cooperating with Synchronization Processor
hardware.

The Start Processor may be thought of as a
transaction processor: it dequeues a start message, does
some processing, and is then ready to dequeue the next
start message. Incoming messages have the form:

msg_start FP, L_S, V

In response to such a message, FP, L_S, and V are loaded
into the Start Processor's SFP, SIP and SV registers,
respectively, after which it begins executing
instructions at L_S. The Start Processor may, of course,
have a general instruction set, but we focus here on the
instructions that it needs to interact harmoniously with
the Data Processor.

The following instruction allows the Start Processor
to store the value SV on the incoming start message into
the destination frame at an offset X identified in the
start processor code:

Start Processor Instruction: store SFP[X], SV

Semantics: Let A = Register [SFP] + X

                          Memory[A] := Register[SV]

The following instruction allows the Start Processor
to cause the Data Processor to begin executing at L_D with
respect to frame FP where L_D and FP are found in start
processor registers:

Start Processor Instruction: post rF, rI

Semantics: Let FP = Register[rF]

                          Let L_D = Register[rI]

                          Post (FP, L_D) to be picked up

                          by the Data Processor

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The following instruction allows the Start Processor to start processing the next message:

      Start Processor Instruction: next_msg
      Semantics: Reload SFP, SIP and SV from
                                  the next incoming msg_start
                                  message

Here is a typical code sequence that executes as a result of a start message that loads label L_S into SIP:

L_S:
      store SFP[X], SV -- store incoming value into
                                frame offset X
      post SFP, L_D -- enable thread L_D with this
                                frame in Data Processor
      next_msg   -- done, handle next message

Synchronization is performed in the Start Processor using synchronization counters in the frames. For example, suppose node N1 sends two arguments to a frame in node N2, using the following two messages:

      msg_start FPx, L_S, V1
      msg_start FPx, M_S, V2

On arrival of each message, the corresponding values are stored in the frame at offsets X1 and X2, respectively. Then, a counter at an offset C (defined by start processor code) in the frame is incremented and compared with the constant 2 (we assume the counter was previously

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initialized to 0). The two messages may be processed in any order; the first message will find the counter equal to 1, and will go to process the next message. The second message will find the counter equal to 2 and will post (SFP,L_D) to the Data Processor which will find the values V_1 and V_2 in memory M for the frame FPx at the offsets X_1, and X_2 identified by start processor and data processor code. Here is the code:

```
LS
    store SFP[X1],SV    -- store incoming value into
                           frame offset X1
    load RO, SFP[C]     -- load counter from frame offset
                           c
    incr RO             -- increment i
    store RO,SFP[c]     -- store it back
    cmp RO,2,RB         -- compare counter value to 2
    jeq RB,NS           -- if equal, go to NS
    next_msg            -- else die; handle next message


MS
    store SFP[X1],SV    -- store incoming value into
                           frame offset X2
    load RO, SFP[C]     -- ...
    incr RO             -- ...
    store RO,SFP[c]     -- same as above
    cmp RO,2,RB         -- ...
    jeq RB,NS           -- ...
    next_msg            -- ...
```

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N_S

    post SFP,L_D -- When both messages handled,

                           enable L_D in Data Processor

    next_msg   -- with this frame

Since we want to allow this kind of synchronization to happen very frequently, we implement the load-increment-store-compare sequence in a single join instruction. Also, the jump to N_S, post and next message instructions are implemented in a single conditional post, next message instruction cpostn.

Readers familiar with dataflow literature will recognize that the input queue of start messages for the Start Processor to which SFP and L_D are posted corresponds to the "token queue" of dataflow architectures.

Global data accesses

A Data Processor in one node can access data in a remote node using remote load and store instructions which move the data to and from the current frame. Such instructions are implemented using split transactions. Once data has been brought into the current frame, it can be manipulated by the Data Processor using conventional instructions. While reading the descriptions below, please refer to Figure 3 for an overview of instructions and messages related to global data accesses.

A remote load instruction fetches data from a remote node by sending a message:

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Date Processor Instruction: rload rA, rI
    Semantics: Let A = Register[rA]
                     Let L_S = Register[rI]
                     Let FP = Register[DFP]
                     Send message: msg_rload A,FP,L_S

The destination node is implicit in the global address A,
which is used to route the message. When the message
arrives at the remote node, it is handled by the RMem
Processor of that node:

    RMem Message: msg_rload A, FP, L_S
    Semantics: Let V = Memory[A]
                     Send message: msg_start FP, L_S,V

We have already seen that the msg_start message is routed
to the node specified by the address FP, and thus it
returns to the node that issued the rload. There, the
code at L_S will store the value V into the frame FP, and
typically a thread (FP,L_D) in the Data Processor will be
enabled to compute with it.
    Note that the rload instruction is also a fork – it
simply initiates the load and continues executing at the
next instruction. Thus, it is possible to initiate many
remote loads before receiving any reply. Further, the
msg_start messages may return in any order – they carry
enough information on them to know how to process them as
they arrive.
    Remote stores are similar. The remote store
instruction initiates a store message from values stored
in registers:

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```
Data Processor Instruction:  rstore rA,rV,rI
Semantics:        Let A = Register[rA]
                  Let V = Register[rV]
                  Let L_S = Register[rI]
                  Let FP = Register[DFP]
                  Send message: rstore A,V,FP,L_S
```

The message is routed to the node identified by the global address A. There, it is handled by the RMem Processor:

```
RMem Message:   rstore A,V,FP,L_S
Semantics:      Memory[A]  :=V
                Send message: msg_start FP,L_S,foo
```

Again, note that the rstore instruction is also a fork - it simply initiates the rstore and continues executing at the next instruction. Later, an acknowledgement comes back to (FP,L_S) (foo is an arbitrary value). The acknowledgement may be used to ensure serial consistency - the code at (FP,L_S) executes under a guarantee that the store has completed.

Rload's and rstore's are just the basic two remote memory operations. It is desirable to extend the repertoire beyond this in order to implement data level synchronization. With each global location that is used with data level synchronization, we associate some extra bits called "presence bits". Two of the states encoded in these bits are called "full" and "empty".

The rIload and rIstore instructions in the Data Processor have the same instruction formats as rload and rstore, respectively, and they generate similar remote

memory messages with msg_rIload and msg_rIstore opcodes.
A msg_rIload arriving at a full location behaves just
like a msg_rload. Arriving at an empty location, it is
deferred (i.e., queued) at that location. The response
is sent later, when a corresponding msg_Istore arrives,
which also deposits a value in the location and marks it
full. These operations allow implementation of
"I-structure" operations which are useful to implement
producer-consumer parallelism (see Arvind and K. K.
Pingali, "I-Structures: Data Structures for Parallel
Computing," ACM Transactions on Programming Languages and
Systems, 11(4):598-632, October 1989).

The rIload and rIstore instructions have the same
instruction formats and behavior as the rload and rstore
instructions, except that the messages that they generate
have msg_rIload and msg_rIstore message opcodes:

Data Processor Instruction: rIload rA, rI
Semantics: Let A = Register[rA]
                 Let L_S = Register[rI]
                 Let FP = REgister[DFP]
                 Send message: msg_rIload A,FP,L_S

Date Processor Instruction: rIstore rA,rV,rI
Semantics: Let A = Register[rA]
                 Let V = Register[rV]
                 Let L_S = Register[rI]
                 Let FP = Register[DFP]
                 Send message: msg_rIstore A,V,FP,L_S

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The interesting difference between these
instructions and rload/rstore is in the treatment of the
messages at the remote node:

RMem Message: msg_rIload A,FP,L_S
Semantics: if full?(Memory[a])
                     Let V = Memory[A]
                     Send message: msg_start, FP,L_S,V
                 else
                     enqueue (FP,L_S) at Memory[A]

Note that if the location is full, an msg_rIload message
behaves just like an msg_rload message. Otherwise, the
message information is queued there to be handled later,
in response to an msg_rIstore message:

RMem Message: msg_rIstore A,V,FP,L_S
Semantics: if empty?(Memory[A])
                     Let queue = Memory[A]
                     Memory[A] :=V
                     For each (FP',M_S) in queue
                        Send message: msg_start FP',M_S,V
                     Send message: msg_start, FP,L_S,foo
                 else
                     error "Multiple writes not allowed"

If the location is empty and no readers are queued there,
it behaves just like an rstore, just storing the value
there. If there are any queued readers, the value is
also sent to them. Finally, if the location is full, it
is a run time error. As in rstore, an acknowledgement
message is also sent.

Remote loads and stores with data-level
synchronization may be used to implement "I-structure"
operations, which permit overlapped operation of the
producer and consumer of a data structure.

The rtake and rput instructions in the Data
Processor have the same instruction formats as rload and
rstore, respectively, and they generate similar remote
memory messages with msg_rtake and msg_rput opcodes. A
msg_rtake arriving at a full location returns the value
just like a msg_rload, but it also marks the location
empty. Arriving at an empty location, it is deferred
just like a msg_iload. A msg_rput arriving at a location
with no deferred msg_rtake's behaves just like a
msg_rIstore, marking the location full. If there are
deferred readers, one reader is dequeued and the value is
sent to it. These operations allow implementation of
atomic updates on remote locations such as shared
counters, shared queues, etc.

The instructions have the same format as rload and
rstore:

        Data Processor Instruction: rtake rA,rI
        Semantics: Let A = Register[rA]
                          Let L_S = Register[rI]
                          Let FP = Register[DFP]
                          Send message: msg_rtake A,FP,L_S

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```
Data Processor Instruction:  rput rA,rV,rI
Semantics:        Let A = Register[rA]
                  Let V = Register[rV]
                  Let L_S = Register[rI]
                  Let FP = Register[DFP]
                  Send message: msg_rput A,V,FP,L_S
```

Again, the interesting difference between these
instructions and rload/rstore is in the treatment of the
messages at the remote node:

```
RMem Message:   msg_rtake A,FP,L_S
Semantics:      if full?(Memory[A])
                    Let V = Memory[A]
                    Send message: msg_start FP,L_S,V
                    Set presence bit of Memory[A] to
                            "empty"
                else
                    enqueue (FP,L_S) at Memory[A]
```

Note that if the location is full, an msg_rtake message
returns the value just line an msg_rload message, but it
also resets the location to the empty state. Otherwise,
the message information is queued there to be handled
later, just like a msg_rIload message.

```
RMem Message:   msg_rput A,V,FP,L_S
Semantics:      if empty?(Memory[a])
                    Let queue = Memory[A]
                    if queue is empty
                      Memory[A]  := V
                      Set presence bit of Heap[A] to
                      "full"
```

```
        else
          Let (FP',M_S) = head(queue)
          Send message: msg_start FP',M_S,V
          Memory[A] := tail(queue)
        Send message: msg_start FP, L_S,foo
      else
          error "Multiple writes not allowed"
```

As in msg_rIstore, if the location in not empty, it is a
run time error. Otherwise, if no readers are queued
there, it behaves just like a msg_rstore or msg_rIstore –
the value is simply stored there and the location is set
to the full state. If there are queued readers, the
first reader is taken off the queue and the value is sent
there; the location remains empty.

Readers familiar with dataflow literature will
recognize that if we omit the Start Processor and Data
Processor in a node, leaving only the RMem Processor, the
local memory and the interface to the network, the
remaining node is precisely an "I-structure Memory"
module.

Inter-thread and inter-frame scheduling control for
better cacheing

So far, we have taken a simplistic view of the POST
instruction in the Start Processor, which posts a new
(FP,L_D) pair to be picked up by the Data Processor when
it executes a NEXT instruction. Figure 1 suggests that
the interface is simply a FIFO queue 32. By being more
sophisticated about this queue, we can improve locality
in the Data Processor, thereby improving the behavior of
any cache that resides between the Data Processor 22 and
the local memory 36.

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The Start Processor can sort the (FP,L_D) pairs according to FP. In other words, for each frame in the current node, it maintains the collection if IPs for that frame. There are various ways to implement this - as a separate table mapping FPs to collections of IPs, as a list of IPs hanging off each frame, or directly as an array within each frame. The exact representation is unimportant, provided the Start Processor can access it. In fact, the responsibility for managing these structures may be shared between the Start and the Data Processors. A specific implementation is discussed in a later section.

Now, the Start Processor can post (FP,L_D) threads to the Data Processor according to a priority scheduling policy. For example, it can give priority to threads that belong to the Data Processor's current frame. This is, in fact, exactly the scheduling policy advocated by Nikhil in his P-RISC compiler [R. S. Nikhil, "The Parallel Programming Language Id and its Compilation for Parallel Machines," _Proc. Workshop on Massive Parallelism_, Amalfi, Italy, October 1989, Academic Press, 1990 (to appear)] and by Culler in his Threaded Abstract Machine (D. E. Culler, A. Sah, K. E. Schauser, T. von Eicken, and J. Wawrzynek, "Fine-grain Parallelism with Minimal Hardware Support: A Compiler-Controlled Threaded Abstract Machine," August 1990). The current frame is thus treated as a "hot frame" where activity is currently focused. To implement this, the Start Processor needs to know what is the current contents of DFP in the Data Processor. This is quite easy to implement.

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A generalization of this principle of hot frames is
to maintain a set of hot frames rather than a single hot
frame. We provide a small "registry" of hot frames
(with, say, 16 entries), with threads from this set given
priority. Registry of frames into this hot set can be
performed either automatically of under explicit software
control. We describe one proposal for such a frame
registry in a later section.

Object Oriented Messages
    The system is also well suited to object oriented
programming. With an object oriented program, an upper
level program specifies methods and objects on which the
methods are to be performed. The actual code of the
methods and the data structures of the objects are hidden
from the higher level software. When a method is called
relative to an object, the lower level software must
locate the code for the method and the data for the
object before the two are processed. In a multiprocessor
system, it may be convenient to locate specific methods
and objects on particular nodes.
    In accordance with the present invention, a message
between nodes may include an identification of the
method, an identification of the object and arguments to
be used in a method. The message is sent to the node at
which the method and object are stored. The message
also includes a return address to the initiating node.
    On receipt of the message, the start processor would
establish a frame and copy the arguments, an object
pointer and the return address into the frame. The start
processor may also look to the object to locate a table

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of method pointers, and then index into the table using
the method number of the message to locate a data
processor instruction pointer. The instruction pointer
and a frame pointer are then provided in the continuation
to the data processor.

Alternatively, the location of the instruction may
be left to the data processor. In that case, the
instruction pointer in the continuation would be to a
handler which locates the instruction.

An Implementation of *T

The *T model creates a clean separation between the
execution of instructions within a thread (the data
processor) and the processing of network messages and the
scheduling of threads (the synchronization processor).
This permits a realization wherein the data processor is
a conventional RISC and the synchronization processor is
a specialized function which behaves much like a
memory-mapped coprocessor to the RISC.

We now present a concrete *T realization centered
around the Motorola M88110, a highly integrated
superscalar RISC microprocessor described by Diefendorff
and Allen in 'Organization of the Motorola 88110
Superscalar RISC Microprocessor", IEEE Micro, 1992. The
synchronization coprocessor documented here is easily
adapted to any microprocessor which supports cache
coherence. As illustrated in Figure 6, a *T node
comprises an unmodified M88110, a memory-mapped
synchronization coprocessor/network interface 26, second
level cache 38, data processor 22, and Local DRAM 36.
The M88110 processor chip 22 includes an instruction

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cache 60 and a data cache 62. Each cache includes a
virtual to physical local address translation buffer 64,
66. Several activation frames may be stored in the
D-Cache 62 and the related blocks of code are stored in
the I-cache 60. The activation frame being processed is
temporarily retained in registers 68. The node is fully
backward compatible such that the synchronization
coprocessor is completely transparent to normal M88110
programs (e.g., UNIX). In terms of hardware protocol,
the synchronization processor acts just like another
M88110 sharing the local bus.

The synchronization processor comprises four
distinct subfunctions:

    o   Message Formatter 40. The message formatter
        maintains a set of memory-mapped registers 41
        that, when written to by an executing M88110
        thread, causes the creation and transmission of
        msg_rload, msg_rstore, and msg_start messages.
        For remote loads and stores, the message
        formatter also includes segment translation
        lookaside buffer hardware 42 for translating
        64-bit global virtual addresses into a
        destination node number and 32-bit local
        virtual address on the destination node.

    o   RMem Processor 28. The RMem processor services
        msg_rload and msg_rstore requests for global
        memory locations which map onto the current
        node. The RMem processor supports imperative
        and many styles of synchronizing data accesses
        (e.g., I-structures, M-Structures).

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o   Start Processor 24. The start processor
    services all msg_start messages directed to the
    current node. The start processor also
    implements the hardware layer of the thread
    scheduler: queues of posted threads
    corresponding to a subset of "hot" frames as
    directed by a frame registry 44.

o   Local Memory Controller 46. The local memory
    controller supports access to locations in
    local virtual address space. The controller
    performs page translation to map the local
    virtual addresses into physical addresses, and
    also provides for block transfers between DRAM
    and the second level cache. The local memory
    controller services local memory read and write
    requests from the start and RMem processors.
    These requests are always in terms of local
    virtual addresses, so the memory controller
    must also support page translation to local
    physical addresses. A simple translation
    lookaside buffer 48 traps the M88110 upon a
    miss. The local memory controller also acts as
    a DRAM controller and is invoked whenever cache
    lines are moved to and from DRAM 36.

The synchronization and data processors
intercommunicate in two ways. First, registers and
queues implemented by the synchronization processor are
memory mapped in the M88110 physical address space. For
example, the M88110 will execute a next instruction by

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reading the head of the thread queue that is filled by
the start processor. Second, the processors share the
same virtual address space and may read and write shared
variables. For example, the start processor will write
the value portion of start messages in activation frame
locations which are subsequently read by a posted thread.
All of this communication takes place over the 64-bit
local data bus. Synchronization processor registers and
queues are directly read and written over this bus, while
shared variables are, in general, found in the second
level cache of DRAM.

In the following section we first describe a scheme
for global addressing which is essential to understand
the functioning of the Message-Formatter. It is followed
by a description of executing dataflow instruction on a
stock M88110. We then present a specific design of the
Synchronization processor.

Global Addresses and Virtual Memory

The message formatter maintains a set of memory-
mapped registers 41 that, when written to by an executing
M88110 thread, causes the creation and transmission of
msg_rload, msg_rstore, and msg_rstart messages. For
remote loads and stores, the message formatter also
includes segment translation hardware 42 for translating
64-bit global virtual addresses into a destination node
number and 32-bit local virtual address on the
destination node.

The M88110 supports 32-bit byte-addresses, yielding
a four gigabyte addresss space. Consider, however, a
possible machine configuration comprising 4K nodes (2^{12})

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with eight megabytes (2^{23}) of local memory per node.
This is 128 gigabytes (2^{37}) in physical memory alone.
Clearly, we require global addresses which are
considerably larger than 32 bits. Our proposal for
supporting a 64-bit global address space while still
retaining efficient and compatible, local addressing is
based upon segmentation. Consider the following:

o   A local Virtual Address (LVA) is a 48-bit
     quantity,

$$LVA = n_{16}:v_{32}$$

     where the v is a virtual address on node number
     n. All local memory references made by a
     processor (e.g., a normal M88110 load or store
     instruction) implicitly refer to its own node,
     so the node part is omitted and only v is
     supplied.

o   A Local Physical Address (LPA) is a 48-bit
     quantity,

$$LPA = n_{16}:p_{32}$$

     where the p is a physical address on node
     number n. As with LVAs, the node part is
     usually implicit (the current node).

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o   A Global Virtual Address (GVA) is a 64-bit
      quantity,

$$GVA = s_{32}:o_{32}$$

where the o is a byte offset within segments s.

An executing program manipulates local and global
virtual addresses. Local references always use local
virtual addresses, while remote references always use
global virtual addresses. Native M88110 page translation
maps local virtual addresses into local physical
addresses. That is, node n decomposes v into a virtual
page frame number and an offset within the page,

$$v = vpn_{20}:offset_{12}$$

where vpn is the virtual page number. The page
translation (PT) on node n maps the vpn into a physical
page number, ppn,

$$vpn \xrightarrow{\text{Page Xlate}} ppn$$

So, the local physical address p is computed as,

$$p = ppn_{20}:offset_{12}$$

where offset is copied from v. In contrast, segment
translation, supported by the synchronization
coprocessor, maps a global virtual address GVA into a
local virtual address LVA. A segment descriptor encodes

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a set of attributes (e.g., valid, writable), how a segment is interleaved across nodes, and the base local virtual address for the segment,

$$\text{segment-descriptor}[s] = (\text{attributes}, \text{interleave-map}, \text{LVA}_{base})$$

For example, suppose that a thread issues an rload of the GVA $A = s_{32}:o_{32}$, where s is the segment and o is the offset within the segment. As illustrated in Figure 7, before formatting an rload_msg, the message formatter 40 fetches the descriptor for s in its segment translation buffer 42. If the descriptor is not found in the segment translation buffer then a trap is elicited on the M88110, which can then, under software control, load the segment descriptor it finds in a global hash table, for example. The mapping information is used through interleave mapping 50 to translate A into the LVA $n_{16}:v_{32}$, where n is a node number and v is a local virtual address on node n. The rload_msg is routed to node n, where the virtual address is translated, by page translation hardware 48 in local memory controller 46, into a local physical address $n_{16}:p_{32}$. The segment translation takes place on the requesting node, while the page translation is performed by the destination node.

Thus, there are three address spaces which map to each other. At each processor there is a local virtual address space which maps into a local physical address space. All translations between those spaces are performed locally. The many individual local vertical address spaces, in association with respective node

designations, map into a global virtual address space
which may be defined by segments and offsets. The data
processor 22 references that global virtual address space
directly through its 64-bit data bus to the message
formatter 40 as discussed below and is thus not limited
by its 32-bit address bus. Translations from the global
address space to a node designation and local virtual
address space are made by the message formatter 40 before
transmitting a message.

The use by the processors 22 of a global address
space, other than the node designations and local address
spaces, distributes global memory accesses during a
routine throughout the multiprocessor system. "Hot
spots" which could cause bottlenecks in interprocessor
communications are thus avoided.

With local use of virtual addresses, the system
allows for a larger physical address space at each
processor. Further, virtual addressing is required by
such standards as Unix. By performing all virtual to
physical translations at the receiving processor rather
than at the transmitting message formatter, the system is
not forced to a universal translation, each processor TLB
48 can be independent.

A continuation is the pair (FP, L_S) comprising a
pointer to an activation frame, FP, and a start processor
code label, L_S. It is particularly useful to pack a
continuation into a single 64-bit word.

Recall, a given activation frame is mapped entirely
onto a single node, and that all address arithmetic on
frames are performed locally on local virtual addresses.
It is thus possible to refer to frames only by their

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local virtual base addresses, which are 48-bit
quantities. Now, assume a convention whereby the first
word in a frame holds a pointer (a local virtual address)
to the base of the start processor program text, SIP_{base}.
This lets us encode L_S as a displacement from the
SIP_{base},

$$L_S = SIP_{base} + \delta$$

where δ is the unsigned displacement. A continuation is
encoded into 64-bits as follows,

$$C = (n_{16}:v_{32}, \delta_{16}) = (FP_{48}, \delta_{16})$$

It is possible to further compress the encoding by
enforcing modulo-alignment constraints on v (e.g.,
cache-line boundaries or larger) and δ. It might be
desirable to reduce it to less than 52 bits, so as to fit
within an IEEE double precision NaN.

Alternatively, a full 24-bits may be retained for
the instruction pointer L_S and the number of bits in the
frame pointer FP can be reduced to 40 bits. The
reduction in frame pointer bits is obtained by
restricting frames to start on multiples of 256 bytes so
that the lower 8 bits are always zero.

Executing Dataflow Instructions on M88110

We now show how the M88110 implements rload, rstore,
and start instructions. These instructions cause the
nonblocking formation and transmission of msg_rload,
msg_rstore, and msg_start messages, respectively. We
also show how the M88110 implements the next instruction.

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The message formatter within the synchronization
processor implements a number of memory-mapped registers.
The main ones are shown below:

mOP	Message operation (rload, rstore, or start)
mA	Destination address GVA or FP
mI	Continuation start code displacement δ
mV	Message value
mDFP	Cached copy of DFP

The mDFP register is a cached copy of the M88110's
DFP register (the current activation frame). This
register is automatically updated when the M88110
performs a next operation (see below).

To send a message, the M88110 first stores a global
address (for rload or rstore) or an activation frame
pointer (for start) in the mA register. Note that the
address is written into the mA register as data. Then,
the start code displacement, δ, is written into the mI
register. The displacement is used to form the return
continuation (together with the contents of mDFP) in the
case of msg_rload and msg_rstore. If the message has a
value-part (i.e., a msg_start or msg_rstore, then the
M88110 stores the value into the mV register. Finally,
the desired operation is written into the mOP register.
Writing to this register automatically causes the
appropriate type of message to be formatted and
transmitted.

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For example, the following M88110 code sequence
implements the rload of 64-bit double value. Assume that
the M88110 register rMF contains a pointer to the message
formatter register set, register rA contains the 64-bit
global virtual address of the word to read, and register
rI contains the start code displacement, δ:


```
L_do_rload.d:
        st.d  rA, rMF, _mA        ;   address to load
                                      into formatter reg
                                      mA

        st    rI, rMF, _mI        ;   start code disp.
                                      into formatter reg
                                      mI

        or    rmsg, _rload.d, r0  ;   formulate rload
                                      command to fetch 64
                                      bits

        st    rmsg, rMF, _mOP     ;   tell formatter to
                                      launch rload
                                      message
```


Note that the M88110 instruction st.d rA, rMF, _mA causes
the contents of the double (64-bit) register rA to be
stored at the address determined by adding the contents
of register rMF to the immediate constant _mA (which we
assume adjusts the address to point to the message
formatter's mA register).

While the above rload sequence is straight-forward,
it is rather inefficient as compared with the native
M88110 load instruction (ld.d). As an optimization, we
use the least significant bits of the addresses from the

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M88110 to pass information from the M88110 to the message
formatter. Suppose that the message formatter decodes a
range of 32-bit local addresses during an M88110 st.d as
follows:

SELECT	δ	msg_op	000
8	16	5	3

The message formatter is selected whenever the
M88110 performs a st.d operation to any address where the
upper eight bits are set to the required SELECT bit
pattern. That is, this feature consumes 1/256 of the
local virtual address space. Here is what happens when
the st.d executes:

mA	←	double value written
mI	←	δ
mOP	←	msg_op

This also causes the message encoded by msg_op to be
formatted and transmitted.

Now, the M88110 can issue a single instruction to
initiate the rload. Assume that the M88110 register rSEL
is all zeros, except for the upper eight bits, which are
set to the message formatter SELECT code. Also assume
that δ is a small constant (<255) called _delta:

L_do_rload.d:

st.d rA, rSEL, (_delta << 8) || (_rload.d << 3) ; initiate rload

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Note that the expression (_delta << 8) || (_rload.d << 3)
is evaluated by the assembler, and is reduced to a 16-bit
instruction immediate. The M88110 rst.d instruction
stores the contents of the 64-bit register rA, which is
assumed to contain the GVA of the location to read, to an
address encoded in the fashion of the table above.

Finally, this is how the message formatter generates
the msg_rload message:

$$A = \text{Register}[mA]$$
$$FP = \text{Register}[mDFP]$$
$$\delta = \text{Register}[mI]$$
$$\hat{n}.\hat{v} = \text{SegmentXlate}(A)$$
$$C = (\text{this\_node.FP}, \delta)$$

Send message: msg_rload n.v,C

The implementation for rstore is similar to rload,
except that we must also supply the value to store. This
is accomplished by writing the value to the message
formatter mV register, and then supplying the address:

```
L_do_rstore.d:
st.d  rV, rMF, _mV                              ; value to store
st.d  rA, rSEL, (_delta << 8) || (_rstore.d << 3); initiate rstore
```

The code assumes that the value to store is in register
rV. The first rst.d writes the value to store into
message formatter register mV. The second rst.d actually
causes the network message to be initiated by supplying
the address to write and the return continuation for the

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write acknowledgement. This is how the message formatter
generates the msg_rstore message:

$$V = Register[mV]$$
$$A = Register[mA]$$
$$FP = Register[mDFP]$$
$$\delta = Register[mI]$$
$$\hat{n}.\hat{v} = SegmentXlate(A)$$

Send message: msg_rstore n.v,V,C

The implementation for start is just like rstore,
only instead of writing the address to store, we supply a
continuation for the remote frame. Assume that M88110
register rRC contains the continuation of the remote
frame:

L_do_start.d:

```
st.d  rV, rMF, _mV                          ; value-part of
                                              start message
st.d rRC, rSEL, (_adj << 8) || (_start.d << 3); initiate start
```

Here, _adj is considered an adjustment to the δ-part of
the supplied remote continuation. Although the
M88110-side looks like an rstore, the response of the
message formatter is quite different:

$$V = Register[mV]$$
$$adj = Register[mI]$$
$$(n.v,\delta) = Register[mA]$$
$$\delta = \delta + adj$$
$$C = (n.v,\delta)$$

Send message   msg_start C,V

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The operand size for rload, rstore, and start can
vary from one to thirty-two bytes, in powers of two. The
operand size is encoded as part of the message operation
stored in the register mOP, and is carried on the
message. E.g., rstore.b stores a byte, rload.s fetches
four bytes, and start.q sends sixteen bytes.

Similarly, memory semantics are also encoded into
rstore and rload messages. E.g., rIload.d fetches eight
bytes according to I-structure semantics. I-structure
and M-structure operations are only defined for
eight-byte operands, or bigger. In the case of larger
operands, i.e., sixteen and thirty-two bytes, I-structure
semantics apply to the entire aggregate. The table below
summarizes.

Operand	Size (Bytes)	Extension	start	rload/rstore Imperative	I-Structure	M-Structure
null	0	.n	√	√		
byte	1	.b	√	√		
halfword	2	.h	√	√		
word/single	4	.w/.s	√	√		
double	8	.d	√	√	√	√
quadword	16	.q	√	√	√	√
octword	32	.o	√	√	√	√

When the M88110 wants to begin executing a new
thread it executes a next instruction which, from its
perspective, is simply the popping of an FP,IP pair from
the synchronization processor's thread queue 32, and then
a transfer of control to the new IP. The synchronization
processor presents the head of the thread queue as a
memory-mapped 64-bit register sQ, which contains the next
FP and IP.

Note that FP and IP are both 32-bit local virtual
addresses. Assume that the M88110 register rQ points to
the synchronization processor register sQ, and that
M88110 register rDFP contains a pointer to the current
activation frame. It is also assumed that M88110
register rDIP is allocated adjacent to rDFP, such that
when rDFP is loaded with a double (64-bit) value, rDFP
receives the most significant thirty-two bits and rDIP
receives the least significant thirty-two bits. Here is
the sequence that M88110 executes to implement next:

```
ld.d rDFP, rQ, 0    ; pop FP,IP pair from head of queue
jmp  rDIP           ; jump to the new thread
```

The act of popping the FP, IP pair from the queue also
has the side-effect of setting the message formatter's
cached version of the current data processor activation
frame (mDFP) to the new FP.

The Synchronization Processor

The RMem processor is a finite-state machine that
consumes msg_rload and msg_rstore messages destined for
the current node, and either responds with a msg_start
back to the requesting processor, or elicits a trap on
the M88110 for handling conditions beyond its capability.
Other than normal imperative operations, the processor
will implement at least the basic layer of I-structure
and M-structure protocol.

Presence bits may be maintained as additional bits
tagged to each word (or a cache line's worth of words),
or as bits packed into 64-bit words in the local virtual

address space. Multiple-deferred readers of an
I-structure or M-structure may be handled through
Monsoon-style request threading, trapping the local
M88110, or local deferred list management. Errors, like
multiple writes, may be handled by responding with a
msg_error, or trapping the local M88110.

Note that the RMem processor never need perform
segment translation, because the frame pointers of the
return continuations are always represented as local
virtual addresses. It simply consults the node-part of
the frame address when formulating a msg_start response.

The start processor handles all msg_start messages
destined for the current node. The start processor
implements the first "layer" of message handling and
synchronization:

1.   Writes the value-part of the start message into an
      offset in the activation frame, the frame also being
      specified by the start message.

2.   Performs a join operation on counter values in the
      activation frame specified by the start message.

3.   Posts ready threads to a queue that can be popped by
      the M88110 when executing a next operation.

There are three primary ways in which an M88110 and
its local Start Processor interact; (1) the M88110 can
execute a rload, rstore, or start which either directly
or indirectly results in a msg_start message destined to
the local Start Processor; (2) in the course of

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processing a msg_start message, the Start Processor
writes activation frame locations which are subsequently
read by an M88110 thread; (3) the M88110 executes a next
instruction which pops the continuation for the next
thread to execute from a queue managed by the Start
Processor.

Of the three modes of M88110-Start Processor
interaction, communication through shared activation
frame locations is the most unstructured. We can
rationalize the communication by establishing a set of
conventions for the usage of storage within a frame.
Logically, we divide an activation frame into four areas:

Activation Frame Area	Start Proc.	M88110
Linkage - IP BASE	Read-Only	R/W
Join Counters	R/W	Read-Only
Message Values	Write	Read
Inter-Thread Values		R/W

Recall, a msg_start message comprises a continuation
and a value,

$$\text{msg\_start} = (FP, \hat{\delta}), V$$

where FP is a pointer to the base of an activation frame,
and V is variable-sized value, from zero to thirty-two

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bytes. The code pointer for the message handler is
computed as,

$$SIP = SIP_{base} + \delta$$

where SIP_{base} is, by convention, stored in the first word
in the current activation frame, i.e., FP[0].

Here are the Start Processor registers 52 which are
automatically loaded upon dispatching to the handler of a
new message:

SIP	Message handler instruction pointer
SFP	Current activation frame base
SV	Message value (MSW)
SV1	Message value
SV2	Message value
SV3	Message value (LSW)

One of the first actions of most every message
handler is to write Message Value registers to offsets in
the activation frame pointed to by SFP.

An important new dimension of *T is an explicit
hierarchy of scheduling data processor threads. In
Monsoon the only control over scheduling is the ability
to force a recirculation of a token; this is key concept
behind a·Monsoon thread. The principle motivation to
extend the control over scheduling beyond the thread
level is to induce temporal locality. Biasing scheduling
across a small subset of frames can enhance hit rates in
the processor data cache 62 and instruction cache.
Biasing scheduling towards threads within a frame permits

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the speculative allocation of temporary registers 68.
That is, if threads related to the same frame are
scheduled one after the other, then the threads can
potentially communicate values through temporary
registers which might otherwise be indeterminate.

Our implementation implements the scheduling
hierarchy through a very simple mechanism called a frame
registry, a small associative table 44 of activation
frame base pointers. When the start processor attempts
to post an FP,IP pair, the frame registry is queried. If
the FP is found in the registry, then the pair is
enqueued into a hardware-managed thread queue. There is
logically one such thread queue for each registered
frame. If the FP is not found in the registry, then a
trap is elicited (probably on the start processor,
though perhaps on the M88110) and the IP is enqueued onto
a software-managed list of ready, but presently-inactive,
frames.

When the M88110 executes a next instruction, it pops
an FP,IP pair from one of the registered frames. The
hardware biases scheduling within the frame by always
giving an FP,IP pairs from the same frame until that
frame's queue is depleted. Only then does the popping
focus on another registered frame. As an option,
"cleanup" and "startup" threads can be executed whenever
the scheduling crosses a frame boundary.

Execution continues in this fashion until all the
queues of the registered frames are empty. When the
M88110 executes a next instruction under this condition,
it is given an "out of work" thread which, presumably,
deregisters the least recently used frame and registers a
frame from the software managed queue of ready frames.

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Figure 8 illustrates a specific implementation of the Start Processor 24. When a message is received, the frame pointer, instruction pointer and value are automatically written in to the SIP register 70 and appropriate registers of the register file 92 through data path 93. Also, the frame pointer is loaded into the frame registry 44. In the implementation shown, it is assumed that the Start Processor instruction pointer SIP is carried by the message. If instead the value δ is carried by the message, an additional stage would be provided to fetch the instruction pointer base and compute SIP.

The instruction pointer is stored in a register 70 through a multiplexer 72. Alternatively, the multiplexer 72 may select the prior SIP incremented by 1 at 74. Instruction fetch logic 76 addresses the instruction cache 78 to retrieve a 32 bit instruction which is stored in instruction register 80. A portion of the instruction is decoded by logic 82 and the decoded instruction is stored in decoded Ir register 84. Ten bits from the instruction stored in register 80 are used to address two operands in a register file 92. The operands in the addressed registers are written through multiplexers 94 and 96 to respective registers 98 and 100. Alternatively, the previous output from the ALU 62 may be written back through one of the multiplexers 94, 96 to one of the registers 98, 100.

Either a constant from the decoded IR register 84 or the value held in the B register 100 is selected by a multiplexer 104 to be operated on along with the value in the A register 98 according to an opcode from the

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register 84. The output from the ALU is stored in a Y
register 106 as the decoded instruction is passed to
register 108. The value from the B register 100 is also
passed to a DB register 110.

When data is to be written into the data cache 112
the Y register 106 carries the cache address and the DB
register 110 carries the data to be stored. Similarly,
the Y register 106 would hold the address when data is to
be written from the data cache 112. Alternatively, the Y
register 106 may carry data which is selected by a
multiplexer 114 to be stored in the data output Q
register 116. As data is stored in the Q register 116,
the decoded instruction is moved from register 108 to
register 118. The data held in Q register 116 may be
written back to the register file at an address taken
from the decoded instruction register 118.

As thus far described, the Start Processor of Figure
8 is a conventional five-stage pipeline processor
including an instruction fetch stage IF, an instruction
decode/operand fetch stage ID/OL, an arithmetic and logic
stage ALU, a data cache stage DC and a writeback stage
WB. The system is modified to include hardware for
testing a count value fetched from the cache 112,
incrementing the value and restoring the value. That
hardware allows for a rapid test to determine whether all
operands have been received for a join operation. If the
test indicates that all operands have been received the
frame pointer and data processor instruction pointer are
directed to the frame registry 44.

Connected in parallel with the cache stage DC is a
frame registry stage FR. As discussed below, when a join

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operation succeeds, the frame registry 44 receives a data processor instruction pointer from register 106 and a frame pointer from register 110 to generate a continuation. The frame registry maintains a queue 32 of continuations to be fetched by the data processor 22 to initiate a new thread of computation. Specifically, the queue 32 includes a set of queues 120, each established for a particular frame. The active frame is selected by a multiplexer 122.

Details of the increment and test logic 119 are presented in Figure 9. In the case of an ordinary cache operation, the address from the Y register 106 is selected by multiplexer 124. If data is to be written into cache it is selected by multiplexer 126. Similarly, when data is to be read out from cache the address from register 106 is selected by multiplexer 124 and the data output from the cache is stored in the Q register 116. A principal operation of the Start Processor is to check the counter value from cache, increment it to indicate that another operand has been received and then restore the incremented value. To that end, the counter value is first retrieved from the cache 112 at an address received from the register 106. That counter value is stored in register 128 and then compared at 130 with the counter threshold value t_c. The value t_c is taken from the decoded instruction register 108 and held in a register 132. If the counter and the threshold value t_c are equal, a join predicate bit is written into a condition code register 134 (Figure 8). In a subsequent conditional post operation, if the predicate bit is set, a continuation is forwarded to the frame registry 44.

The counter value retrieved from cache 112 and held
in register 128 is incremented at 136 and the incremented
value is stored in register 138. That value is then
written back through multiplexer 126 into the counter
location in cache 112 previously accessed. To again
access that same location, the address is delayed in
registers 140 and 142 and then selected by multiplexer
124 as the incremented value is selected by multiplexer
126.

Figure 10 illustrates processing of a start message
by the processor of Figure 8. The table indicates the
stage in which each instruction is being processed at
successive time steps. With reference to the join
operation, in the ALU stage the frame pointer taken from
the message and held in the register file is added to a
counter pointer which is common to all messages and held
in the register file. In the data cache stage the
counter value is read from the cache 112. As illustrated
in Figure 9, that value is incremented as a comparison is
made to the value t_c in the decoded instruction. The
incremented value is then written back to the cache. If
the comparison indicates that all arguments are on hand,
the join predicate bit (Figure 9) is applied to register
134.

As the join instruction is being decoded, the double
word store instruction of this code is fetched from the
instruction cache. In the ALU stage, that instruction
computes the address in cache at which the operand value
is to be stored. Specifically, it adds the frame pointer
value received in the message with a value r carried by
the instruction. In the data cache stage, the value V

received in the message and stored in the register file
is written from the DB register 110 into the cache 112 at
the address computed by the ALU and stored in the Y
register 106.

As the double word store instruction is being
decoded, a conditional post instruction is fetched from
the instruction cache 78. At the ALU stage, the DIP of a
continuation is computed from the IP base stored in the
register file and an offset from the decoded instruction,
and the DIP is placed in register 106. The frame pointer
FP is stored from the register file into register 110.
In the next step, if the predicate bit had previously
been set from the join operation, the continuation is
forwarded to the frame registry from registers 106 and
110. If not, the condition has not been met and there is
no further operation.

A no-operation is included in the next line of code.
This allows for a time step in the event of a jump due to
a registry fault. The registry fault occurs if there is
set if there is a successful join operation in which the
predicate bit is set but the frame pointer is not
included in the registry table. The frame registry is
loaded with the frame pointer when the message is
received so the table can be checked ahead of time (step
5 in Figure 10). In the event of a registry fault there
is a jump in time step 5 which delays the next join
instruction.

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Single Instruction Sequence Embodiments

A significant advantage of the embodiments of the
invention described above is that the synchronization and
data processors may operate in parallel, thus reducing
the processing time at any node. However, the
synchronization processes and data processes may be
processed as a single sequence of instructions. Such a
system loses the full parallelism yet retains other
advantages such as ease of synchronization and scheduling
without loss of efficiency in processing of longer
threads.

The synchronization processor and the data processor
are programmable processors which sequence through
instructions designated by the messages and the
continuations, respectively. Both types of processes can
be performed by a single processing unit so long as means
is provided for scheduling the respective message and
continuation processing blocks of code after each block
of code is terminated. To that end, as each block of
code ends, be it message processing code or continuation
processing code, the processor need only look to the
respective message and continuation queues and assign a
priority scheme for selecting the next process from one
of those queues. In order to minimize interruptions to
the network, it is preferred that messages be given
priority for processing over continuations.

Figure 11 illustrates the general states of a single
microprocessor operating in such a fashion. So long as
the message queue is not empty as at 200, 202 and 203,
the processor continues to retrieve messages from the
message queue and process those messages at 204. In

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particular, as in the previous embodiment, the messages
include instruction pointers and frame pointers to
initiate synchronization routines with respect to the
designated frames. As before, the synchronization code
blocks processed from the message may result in the
generation of continuations stored in the continuation
queue. Once all available messages have been processed
at 204, and if the continuation queue is not empty, the
system moves at 205 to the data processing state 206
where the next continuation to be processed is retrieved
from the continuation queue. At the end of each thread
of computation, the system again checks the state of the
queues. So long as the message queue is empty and the
continuation queue is not empty, the system continues at
208 to retrieve continuations from the continuation queue
to process the corresponding threads of computation. If
a message should arrive, after the completion of a thread
of computation the system would return at 202 to the
message processing state 204. On the other hand, if both
queues should be empty after processing of either a
message or a continuation, the system would proceed at
210 or 214 to the idle state 212. In the idle state, the
system would continue to loop at 213 through a background
process until a message is received at 203.

     From the above, it can be seen that no special
interrupts are required to process messages as they are
received so long as the data processing threads of
computation are sufficiently short that they end before
the message queue becomes full. To increase the speed of
operation, simple logic can be provided to check the
states of the queues and to select the message or

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continuation to be next processed. The data processor
then proceeds through the selected block of code without
regard for whether the instruction and frame pointers are
derived from a message or from a continuation. In fact,
internal messages within a node may be treated as
continuations in the continuation queue rather than as
messages in the message queue.

Single Instruction Sequence, Coprocessor Embodiment

The Motorola 88110 Microprocessor uses a superscalar
RISC processing approach in which special purpose RISC
hardware units receive instructions from a single
instruction sequencer. That microprocessor is described
in detail by Diefendorff and Allen in "Organization of
the Motorola 88110 SuperScalar RISC Microprocesser," IEEE
Micro, 1992. An extension of that microprocessor to
include message processing units in accordance with the
present invention is presented in Figure 12. As in the
standard 88110 chip, code issue units 220 simultaneously
issue two instructions at a time from a single code
sequence to any two of several special purpose processing
units on a source bus 222. Specifically, the units
include two integer units 224, three floating point units
226, two graphics units 228, and a load/store unit 232.
Each instruction may operate on two operands in shared
register files 230. Outputs from the various units are
applied through a write-back bus 234 to the register
files 230. Each instruction to the various units may
provide a single operand return to the register file.
Instructions are retrieved from memory by the code issue
units 220 through a bus interface unit 236 and a code

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cache 238 with memory management unit 240. Data is retrieved from and returned to memory through the bus interface unit 236 and a data cache 242 with memory management unit 244.

In accordance with the present invention, additional synchronization coprocessor units 246 are provided on the source and write-back buses 222 and 234. Those units retrieve and transmit messages to a network through a message interface 248. The message units operate on their specific instructions received from the code issue units 222 just as the other units operate on their own specific instructions.

Further detail of the synchronization units 246 is presented in Figure 13. The units include two processors, a message processor 250 and a schedule processor 252. The message processor processes transmit instructions which can read data from the register files and store that data in a transmit buffer of a transmit queue 254. The message processor also causes the completed message to be transmitted through the message interface 248. The message processor 250 also handles receive instructions to read words from the receive buffer and write those words into the register files 230. The receive queue comprises, for example, 16 buffers each capable of holding a message of 4 to 24 32-bit words.

The protocol of the messages is as illustrated in Figure 14. The first layer comprises the route and CRC fields. The formats of these fields are known to all the network hardware. The route is the physical network address which the message coprocessor automatically translates from the node virtual network address whenever

the node word is stored in the transmit buffer. The
second layer comprises the message handler local
microthread descriptor. With respect to this embodiment,
the term microthread descriptor is used to reference the
instruction pointer and frame pointer of either the
message or the continuation. Both are processed under
control of the common code issue units 220. However, the
message handler local microthread descriptors are carried
by the messages in the transmit and receive queues;
whereas the continuation microthread descriptors are
stored in the continuation queue 258 handled by the
schedule processor 252. The third layer is the return
address packed global microthread descriptor which
identifies the frame to which the return message is to be
returned. Finally, the message includes a value layer
266.

The schedule processor 252 maintains a continuation
queue 258 of microthread descriptors received from the
general register file through scheduling instructions.
Those instructions may be included in code blocks for
processing messages or code blocks processing threads.
The schedule processor also selects a microthread
descriptor to be stored in the current microthread
descriptor register 268 of the general register file.
The code issue units 220 look to that register for the
instruction pointer and frame pointer for the next block
of code to be processed. The scheduler selects a
microthread from one of the following: the next message
of the receive buffer 256, the continuation queue 258, a
microthread descriptor supplied as an input to the
scheduler instruction, or a microthread descriptor
register file 270.

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The scheduler contains a fixed-priority arbiter.
Each scheduling instruction uses this arbiter to select
the highest priority microthread that is enabled by the
scheduling instruction and that is also requesting
service. Each scheduling instruction has a default
request that causes a specified microthread to be
selected if there is no higher priority request.

The scheduling priorities are:

1   microthread descriptor register 0

2   microthread descriptor register 1 -- stack
     overflow

3   microthread descriptor register 2 -- user
     "interrupt" pin

4   receive message handler, high priority

5   microthread descriptor register 3

6   microthread descriptor register 4 -- poll
     message return

7   microthread descriptor top of continuation queue

8   microthread descriptor register 5

10   microthread descriptor register 6

11   microthread descriptor register 7 -- background

Each of the seven microthread descriptor registers
has an associated request bit. Some of these request bits
are set and reset by hardware, as indicated in the
priority list. The background microthread always
requests service. The rest of these microthread
descriptor registers are usable however the scheduling
software desires. Those request bits are set when the
store microthread instruction stores a descriptor into
the register, and the request bits are reset when the
scheduling instruction selects that descriptor.

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From these priorities, it can be seen that the stack overflow microthread descriptor will be selected with high priority. That descriptor calls the process which transfers messages from an overflowing receive queue 256 into software controlled memory storage. It can also be seen that the high priority receive message handler, taken from the receive queue 256, has a higher priority than the microthread descriptor at the top of the continuation queue 258. This results in the above-mentioned preference for clearing the network over local processing of continuations.

The poll message return register allows the compiler to use a poll instruction to poll the message queue for incoming messages. This allows the compiler to put out long microthreads without causing a backup at the receive queue.

Conclusion

Conventional microprocessors are excellent at executing single threads, but do not handle long latency operations or synchronization operations well. Consequently, unless we carefully craft our programs to minimize communication, a massively parallel machine built with these components is likely to have poor utilization at each node.

Data flow processors have complementary strengths and weaknesses - they are very good at handling long latencies and providing cheap synchronization, but have poor single-thread performance. Consequently, a workstation built out of such components is not likely to be competitive; therefore, such processors are not likely to become commodity parts.

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We believe that the systems described here embody the first proposed architecture that can execute single threaded programs as efficiently as conventional microprocessors, execute fine-grain parallel programs as efficiently as dataflow processors, and provide a smooth spectrum of operating points in between.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

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CLAIMS

1. A data processing system comprising:

    a data processor for processing threads of computation, threads of computations including operations to generate messages for initiating new threads of computation; and

    a synchronization coprocessor for responding to messages and indicating to the data processor when a new thread of computation may be performed, the data processor initiating processing of the new thread of computation after the synchronization coprocessor indicates that the new thread of computation is ready to be performed.

2. A data processing system as claimed in Claim 1 wherein the synchronization coprocessor comprises a queue to which continuations are posted to serve as indications to the data processor that a thread of computation may be initiated.

3. A data processing system as claimed in Claim 2 wherein the continuations comprise a pointer to an activation frame and a pointer to a data processor instruction.

4. A data processing system as claimed in Claim 2 or 3 wherein the queue presents continuations according to priority to continue processing active frames.

5. A data processing system as claimed in any of Claims
   1-4 wherein a message comprises a pointer to an
   activation frame and a pointer to an instruction
   sequence.

6. A data processing system as claimed in any of Claims
   1-5 wherein each of plural data processing nodes
   operates on a local virtual address space, and each
   node comprises means for translating from the local
   virtual address space to a local physical address
   space, each data processor generating a global
   virtual address space to access an address in a
   remote node, and each node comprising means for
   translating the global virtual address to a node
   designation and a local virtual address of the
   remote node.

7. In a multiprocessor system comprising a plurality of
   processing nodes as claimed in any preceding claim,
   wherein the synchronization coprocessor processes
   messages from the same node and other nodes of the
   system, stores values from the messages as operands
   for threads of computation, determines when all
   operands required for a thread of computation have
   been received and provides an indication to the data
   processor that a thread of computation may be
   initiated, the data processor nonsynchronously
   initiating processing of a thread of computation
   after completion of a prior thread of computation in
   response to the indication from the synchronization
   processor.

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8. A data processing system comprising:

a continuation queue of continuations which identify blocks of code sequences to be performed with respect to frames of data;

a message queue of messages which identify blocks of code sequences to be performed with respect to frames of data; and

data processing means for processing individual blocks of code sequences identified by continuations from the continuation queue as threads of computation, threads of computations including operations to generate messages for initiating new threads of computation, and for processing individual blocks of code sequences identified by messages from the message queue as message handlers.

9. A data processing system as claimed in Claim 8 wherein a continuation comprises a pointer to an activation frame and a pointer to an instruction sequence.

10. A data processing system as claimed in Claim 8 or 9 wherein a message comprises a pointer to an activation frame and a pointer to an instruction sequence.

11. A data processing system as claimed in any of Claims 8-10 wherein the continuation queue presents continuations according to priority to continue processing active frames.

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12. A data processing system as claimed in any of Claims
     8-11 wherein the data processing means comprises
     separate coprocessors for processing continuations
     and messages.

13. A data processing system as claimed in Claim 12
     wherein the coprocessors operate simultaneously on
     separate code sequences.

14. A data processing system as claimed in any of Claims
     8-13 wherein each of plural data processing nodes
     operates on a local virtual address space, and each
     node comprises means for translating from the local
     virtual address space to a local physical address
     space, each data processing means generating a
     global virtual address space to access an address in
     a remote node, and each node comprising means for
     translating the global virtual address to a node
     designation and a local virtual address of the
     remote node.

15. A method of data processing comprising:
         storing continuations in a continuation queue,
     the continuations identifying blocks of code
     sequences and frames of data on which the code
     sequences are to be formed;
         storing messages in a queue, the messages
     identifying blocks of message handling code
     sequences and frames of data on which the message
     handling code sequences are to be performed; and

processing blocks of code sequences identified
by the continuations and messages without
interruption as additional continuations and
messages are queued, each code block ending with an
instruction to select another continuation or
message for processing of a respective block of code
sequences.

16. A method as claimed in Claim 8 comprising separate
continuation and message queues, the processing of
blocks of code sequences identified by messages
generating continuations to be stored in the
continuation queue.

17. A method as claimed in Claim 15 or 16 comprising
processing the continuations and messages in
separate processors.

18. A multiprocessor system comprising a plurality of
processing nodes, each processing multiple threads
of computation, each node comprising a data
processor for processing threads of computation and
generating messages to remote nodes, each data
processor operating on a local virtual address
space, and each node having means for translating
from the local virtual address space to a local
physical address space, each data processor
generating a global virtual address to access an
address in a remote node, and each node comprising
means for translating the global virtual address to
a node designation and a local virtual address of
the remote node.

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FIG. 1

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FIG. 2

FIG. 3

```
        store O, DFP(c1)
        store O, DFP(c2)
        load DFP(YP), rYP
LOOP:
        load DFP(YLim), rYLim
        cmp  rYLim, rYP, rB
        jgt  rB, DONE

        load  DFP(XP), rXP
        rload rXP, L1s
        rload rYP, L2s
        add 1, rXP,  rXP
        store  DFP(XP), rXP
        next
```

```
L1s:
        store SFP(XI), SV
        jump L3s
```

```
L2s:
        store SFP(YI), SV
        jump L3s
```

```
Ld:
        store O, DFP(c1)
        load DFP(A), rA
        load DFP(XI), rXI
        load DFP(YI), rYI
        load DFP(YP), rYP
        mult rA, rXI, r1
        add r1, rYI, r2
        rstore rYP, r2, L4s
        add 1, rYP, rYP
        store DFP(YP), rYP
        jump LOOP
```

```
L3s:
        join c1,2,Ld
        next_msg
```

```
DONE:
        next
```

```
L4s:
        join c2,N,OUT
        next_msg
```

```
OUT:
        · · · loop sequel · · ·
```

FIG. 4

```
        store 0, DFP(c1)
        store 0, DFP(c2)
        load DFP(XP),   rXP
        load DFP(YP),   rYP
        load DFP(A),    rA
        load DFP(YLim), rYLim
LOOP :
        cmp  rYLim, rYP, rB
        jgt  rB, DONE
        rload  rXP,  L1s
        rload  rYP,  L2s
        add 1, rXP,  rXP

        load  DFP(c1), rC1
        cmp rC1, 2, rB
        jeq  rB, L2d
```

```
L1s:
        store SFP(XI), SV
        jump L3s
```

```
L2s :
        store SFP(YI), SV
        jump L3s
```

```
        store DFP(YP),  rYP
        store DFP(XP),  rXP
        start SFP,L3s,0
        next
```

```
L3s :
        join c1, 3, L1d
        next_msg
```

```
L1d:
        load DFP(XP),    rXP
        load DFP(YP),    rYP
        load DFP(A),     rA
        load DFP(YLim),  rYLim
```

```
L2d :
        store DFP(c1),  0
        load DFP(XI), rXI
        load DFP(YI), rYI
        mult rA,  rXI, r1
        add r1,  rYI, r2
        rstore   rYP, r2, L4s
        add 1,  rYP, rYP
        jump LOOP
```

```
L4s :
        join c2, N, OUT
        next_msg
```
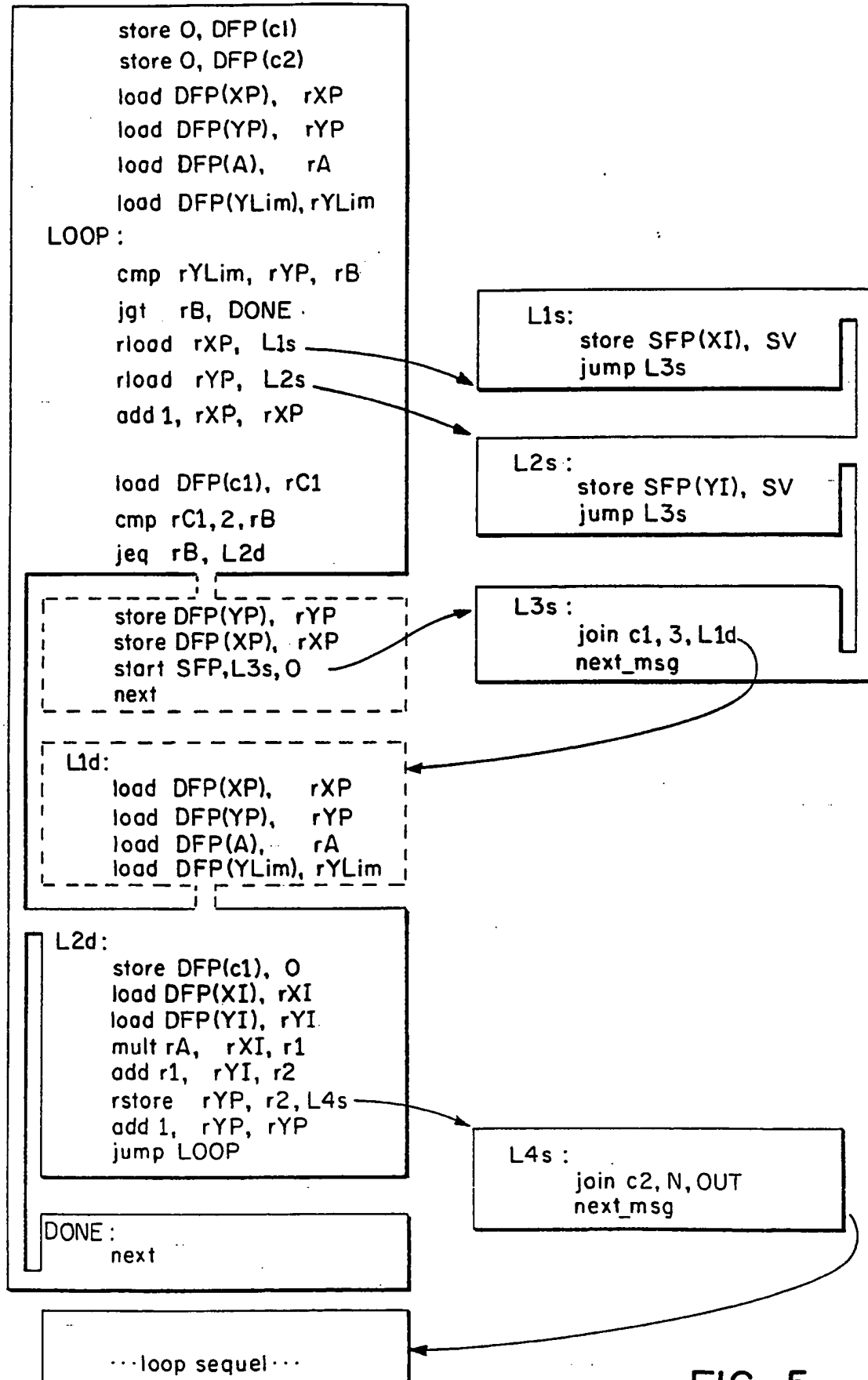
```
DONE :
        next
```

```
···loop sequel···
```

FIG. 5

5/10

FIG. 6

6/10

FIG. 7

FIG. 8

8/10
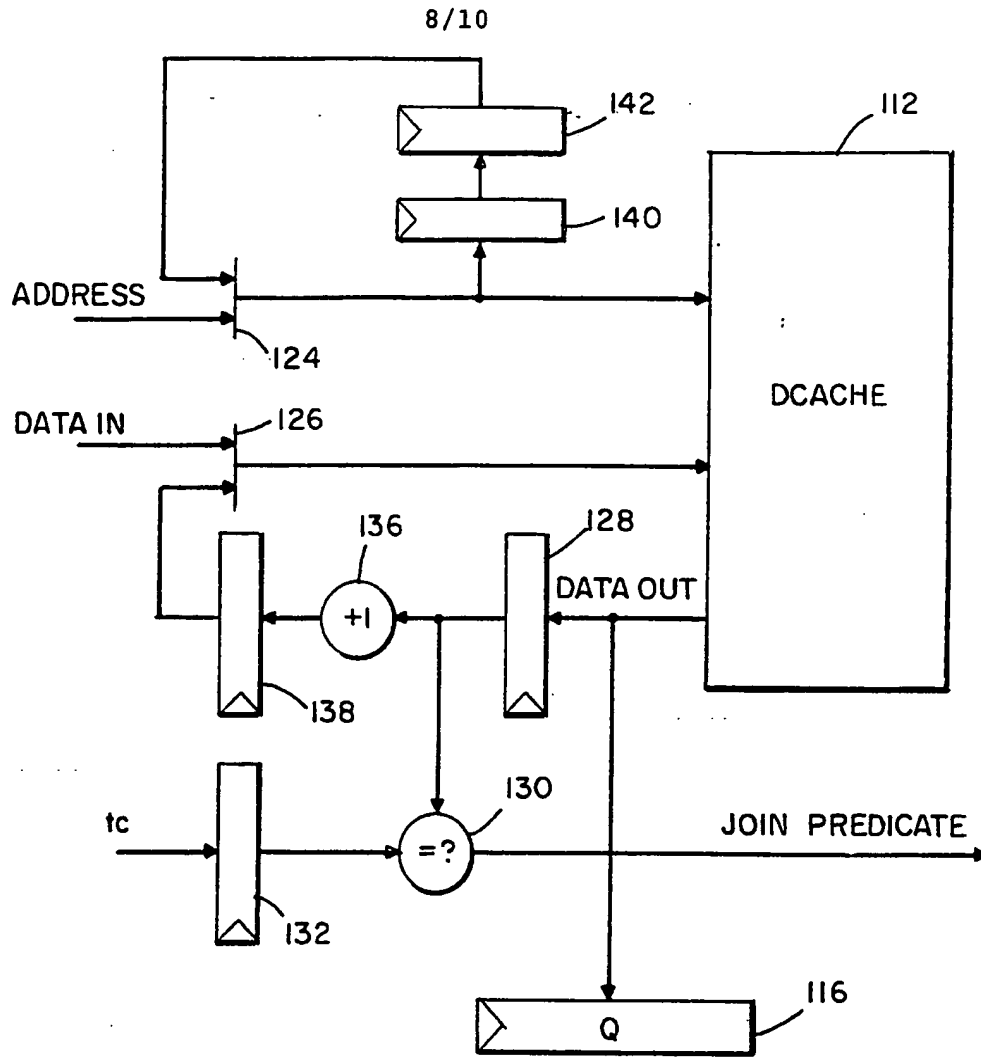
FIG. 9

FIG. 10

TIME STEP	1	2	3	4	5	6	7	8
Ls:								
join [rFP+ctr], t_c	IF	ID	ALU	DC	INC	DC		
st.d [rFP+r], r$\underline{V}$		IF	ID	ALU	DC	[WB]		
cpostn rFP, r IPbase +offset			IF	ID	ALU	FR	[WB]	
nop				IF	ID	ALU	[DC]	[WB]
$\overset{\wedge}{Ls}$								
join [r$\widehat{FP}$+ctr], $\overset{\wedge}{t_c}$					IF	ID	ALU	DC
FR FAULT:					IF	ID	ALU	DC

MESSAGE QUEUE
NOT EMPTY

MESSAGE QUEUE EMPTY
CONTINUATION QUEUE NOT EMPTY

204

206

208

200

205

PROCESSING
MESSAGES

202

PROCESSING
DATA THREADS

MESSAGE QUEUE
NOT EMPTY

203

MESSAGE QUEUE EMPTY
CONTINUATION QUEUE
NOT EMPTY

BOTH QUEUES
EMPTY

214

BOTH QUEUES
EMPTY

IDLE

210

213

212

BOTH QUEUES
EMPTY

FIG. 11

234 222

224

BRANCH
CACHE

INTEGER
UNITS

240

226

MMU

CODE
CACHE

CODE
ISSUE
UNITS

FLOATING
POINT
UNITS

238

220

BUS INTERFACE UNIT

230

228 248

236

244

REGISTER
FILES

GRAPHICS
UNITS

MESSAGE INTERFACE

MMU

SNOOP

232

246

DATA
CACHE

LOAD
STORE
UNIT

SYNCH
UNITS

242

FIG. 12   SUBSTITUTE SHEET

268

CURRENT MICROTHREAD
DESCRIPTOR REGISTER

222, 234

246 →

MESSAGE
PROCESSOR | 250

SCHEDULE
PROCESSOR | 252

MICROTHREAD
DESCRIPTOR
REGISTERS
0 - 7

254

XMIT
QUEUE

256

REC'V
QUEUE

258

CONTINUATION
QUEUE

270

248

MESSAGE
INTERFACE

FIG. 13

260

ROUTE

262

MESSAGE HANDLER
LOCAL MICROTHREAD DESCRIPTOR

264

RETURN ADDRESS
PACKED GLOBAL MICROTHREAD DESCRIPTOR

FIG. 14

VALUE

266

CRC

261